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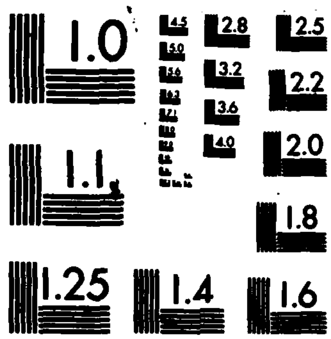

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Study of the Effects of Metallurgical Factors
on the Growth of Fatigue Microcracks

FINAL REPORT

James Lankford

January 1984

Contract No. DAAG29-80-K-0034

Southwest Research Institute
San Antonio, Texas

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The micromechanics of crack tip yielding are characterized for large and small fatigue cracks in aluminum alloys. Techniques used included selected area electron channeling and stereoimaging strain analysis. The anomalous fast growth of small fatigue cracks correlated with greater crack tip strains and displacements, and lower crack opening loads, for microcracks as compared with large cracks. Microcrack growth rate perturbations were modeled in terms of grain boundary induced reductions in crack tip strain.

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I. Statement of Problem

This report summarizes the results of a three-year research program aimed at determining the physical basis for the apparently anomalous growth behavior of small fatigue cracks.[1-3*] In this context, it is necessary to define certain terms. By "physical basis" is meant the influence of metallurgical microstructure, environment, and alloy chemistry upon microcrack tip displacement, deformation, and extension. The growth of small cracks is "anomalous" in the sense that they often are observed (Figure 1) to grow at rates ($^{da}/dN$) greatly different (by as much as several orders of magnitude) from those predicted by tests carried out on large through-cracks at equivalent cyclic stress intensities (ΔK). Finally, cracks are considered "small" when their dimensions are of the same order of size as the material microstructure or a localized plastic zone in which they may reside, or when they are much smaller than the minimum specimen dimension.

II. Summary of Program

Precipitation hardened 7000-series aluminum alloys have been emphasized in the program. Two types of specimen[4] were studied, i.e., one containing single-edge-notched through cracks ("large" cracks), and a second design in which "small" (~15 μm long), half penny-shaped cracks were initiated at inclusions on smooth surfaces. In order to characterize crack tip behavior, special techniques were required.

Selected area electron channeling pattern analysis was used to map out the sizes and shapes of crack tip plastic zones for both large and small cracks. Information still closer to the tips was obtained by use of a servo-controlled hydraulic loading stage[5] which operated inside the scanning electron microscope. By appropriately analyzing[6] the resulting crack tip displacement data, it was possible to determine crack tip opening displacement, crack tip opening load, crack tip strain distribution (Figure 2), and crack tip opening mode. Principal results, for peak- and over-aged 7075 Al, can be summarized as follows (details are provided in the publications listed in the next section):

1. Small cracks grow faster than large cracks at equivalent cyclic stress intensities, and they grow below the large crack threshold stress intensity (ΔK_{TH}) (Figure 1).

2. Monotonic plastic zone sizes for large and small cracks correlate according to ΔK^2 (Figure 3).

3. Cumulative microstrains in grains in which small cracks nucleate and grow at cyclic stresses on the order of 80% yield strength do not exceed 0.003; the grains are basically elastic.

4. The ratio of plastic zone size to crack size is approximately unity for microcracks, while for large cracks, the ratio is <<1.

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*Superscripts refer to Bibliography.

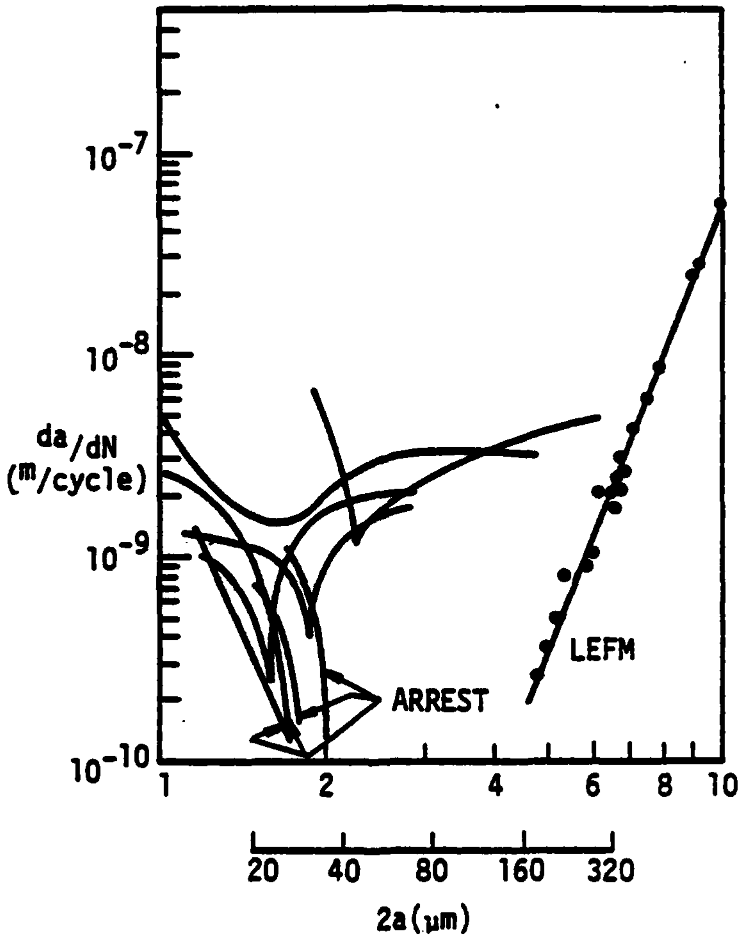

Figure 1. Growth of fatigue microcracks in dry nitrogen compared with large crack (LEFM) results.

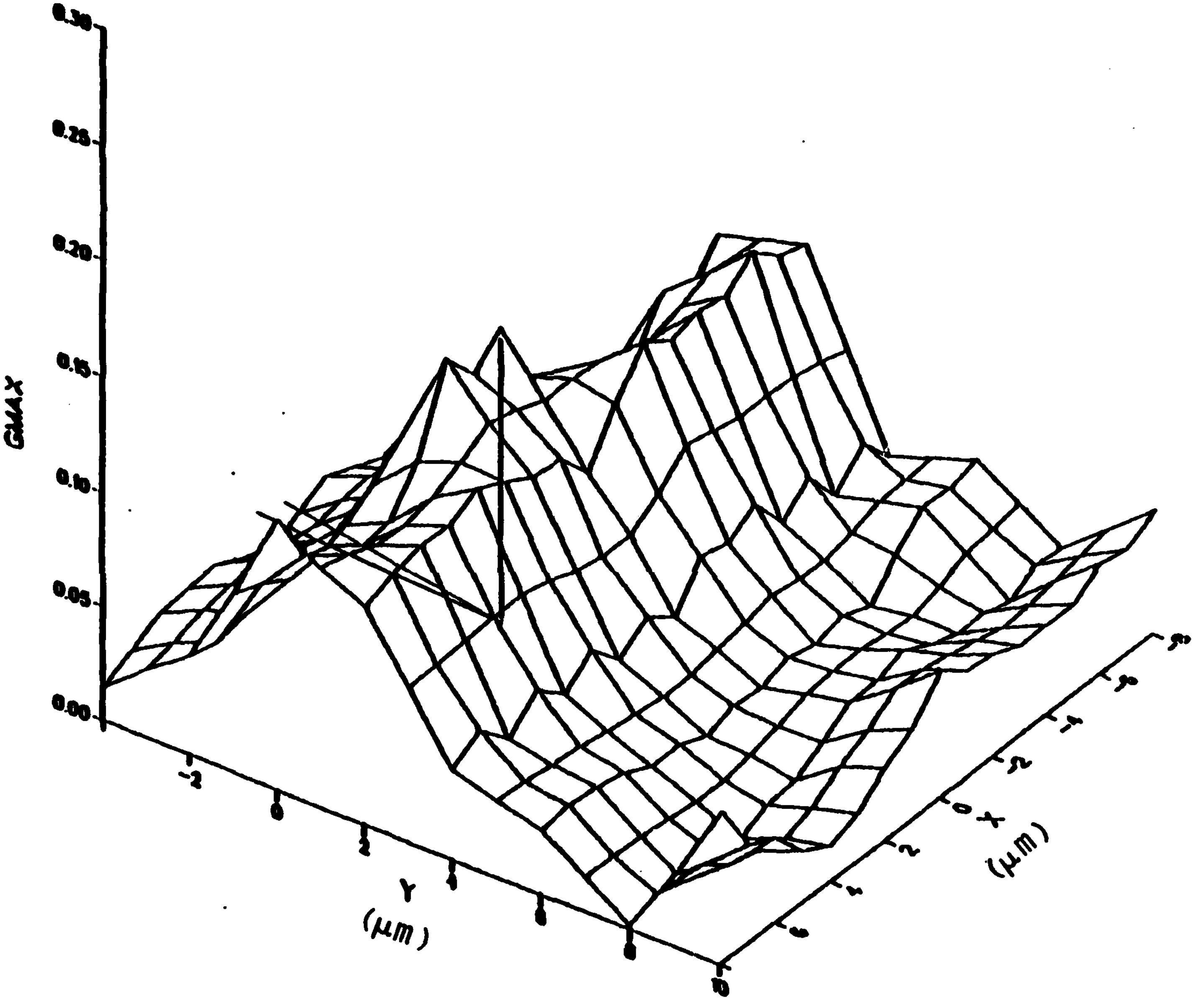

Figure 2a. Maximum shear strain distribution about the tip of a small crack 206 μm in length loaded to $\Delta K = 4.65\ MN/m^{3/2}$.

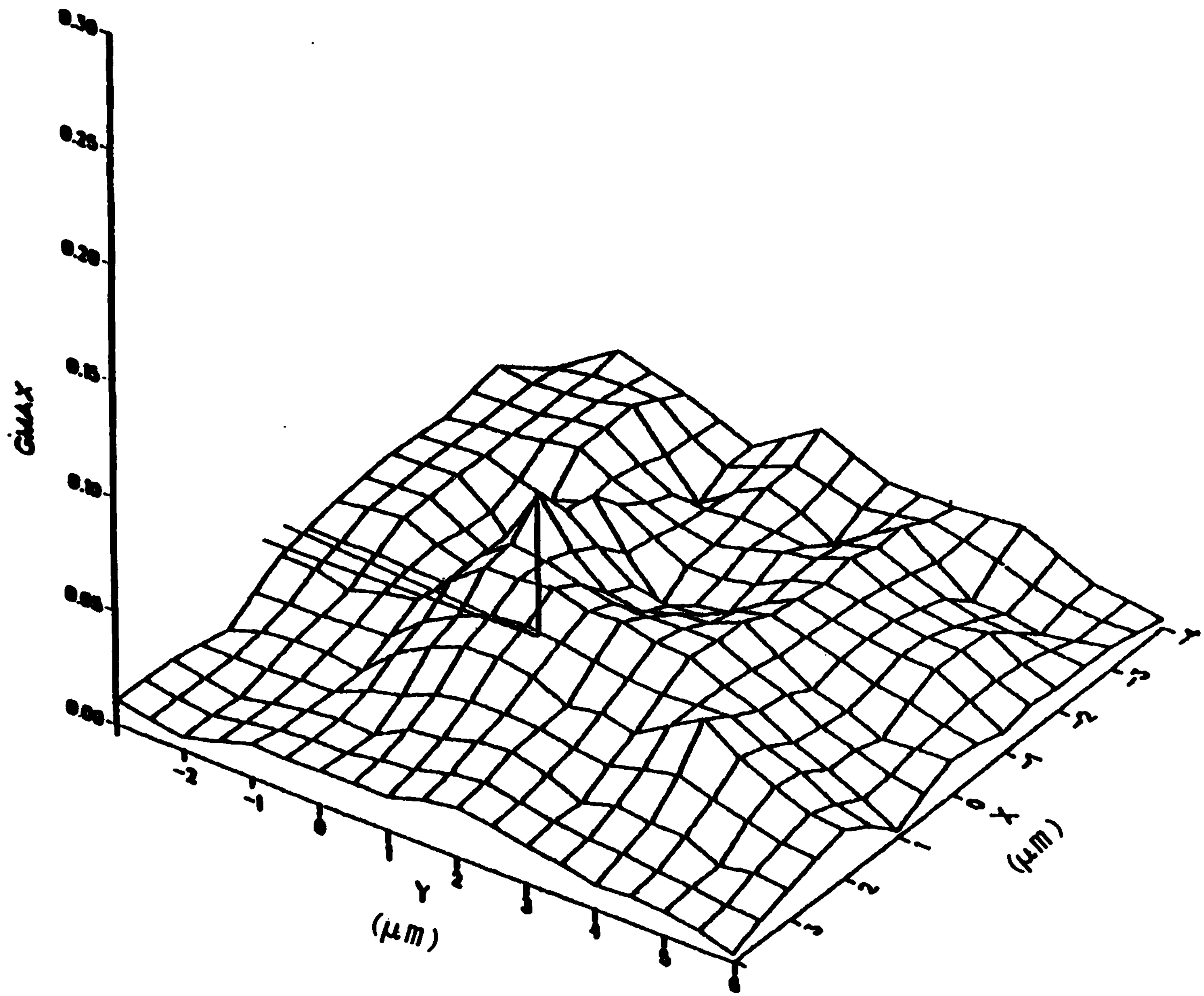

Figure 2b. Maximum shear strain distribution about the tip of a large crack loaded to $\Delta K = 5\ MN/m^{3/2}$.

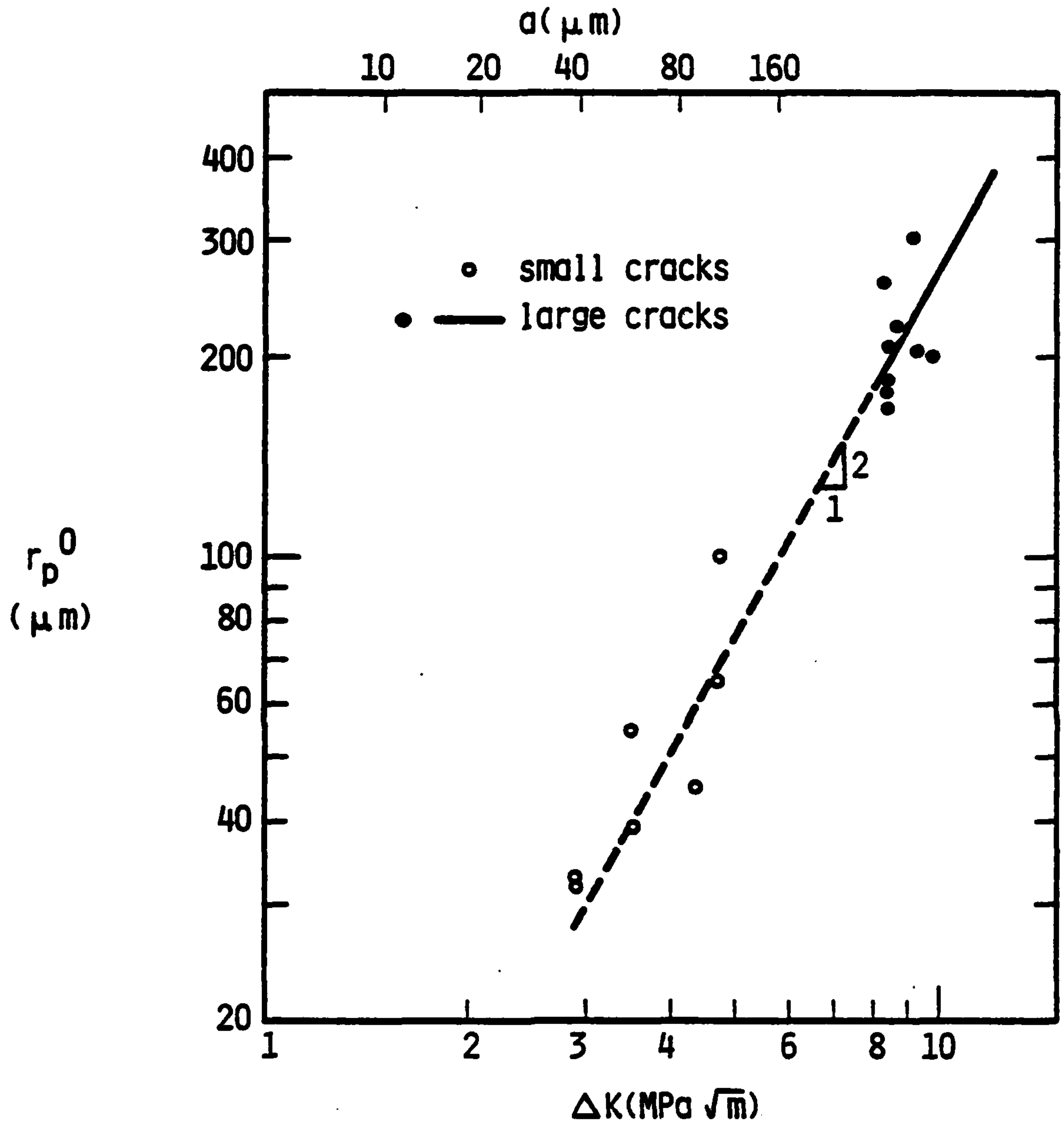

Figure 3. Plastic zone size ahead of crack tip versus cyclic stress intensity. Lines shown are extrapolations of large crack data assuming a slope of 2.

5. For large cracks, the crack tip opening load approaches the maximum cyclic load (P_{max}) as the threshold is neared, while microcracks open well below P_{max} even for $\Delta K<\Delta K_{Th}$ (Figure 4). This probably accounts for the growth of microcracks below the large crack threshold, and partly accounts for the rapid average growth rates of small cracks.

6. Crack tip strain (Figure 2) and crack tip opening displacements for microcracks exceed those of large cracks at equivalent stress intensities, at least partly accounting for the more rapid growth of small cracks.

7. The distribution of strain at the tips of small cracks is different than that for a large crack (Figure 2).

8. Crack tip strain correlates well with crack tip opening displacement for large cracks but not for small cracks.

9. Large cracks grow faster in air than in vacuum. Small cracks tested in air and dry nitrogen (nominally equivalent to vacuum) grow at approximately the same rates. The absence of environmental influence is thought to be only apparent, a change to an inherently slower mode of growth in air offsetting the crack-accelerating influence of moisture.

10. Superimposed on the rapid growth of small cracks are transient periods of arrest or retardation.

11. These arrest periods have been accounted for quantitatively by a model based upon the concept of a reduction in crack tip strain at grain boundaries.

12. However, empirical adjustments to ΔK based on crack closure and plastic constraint are unable to correlate the growth rates of large and small cracks.

13. For small cracks, small-scale yielding assumptions are violated, and similitude is lost.

14. The cyclic stress intensity may be an inappropriate choice as the driving force for small cracks.

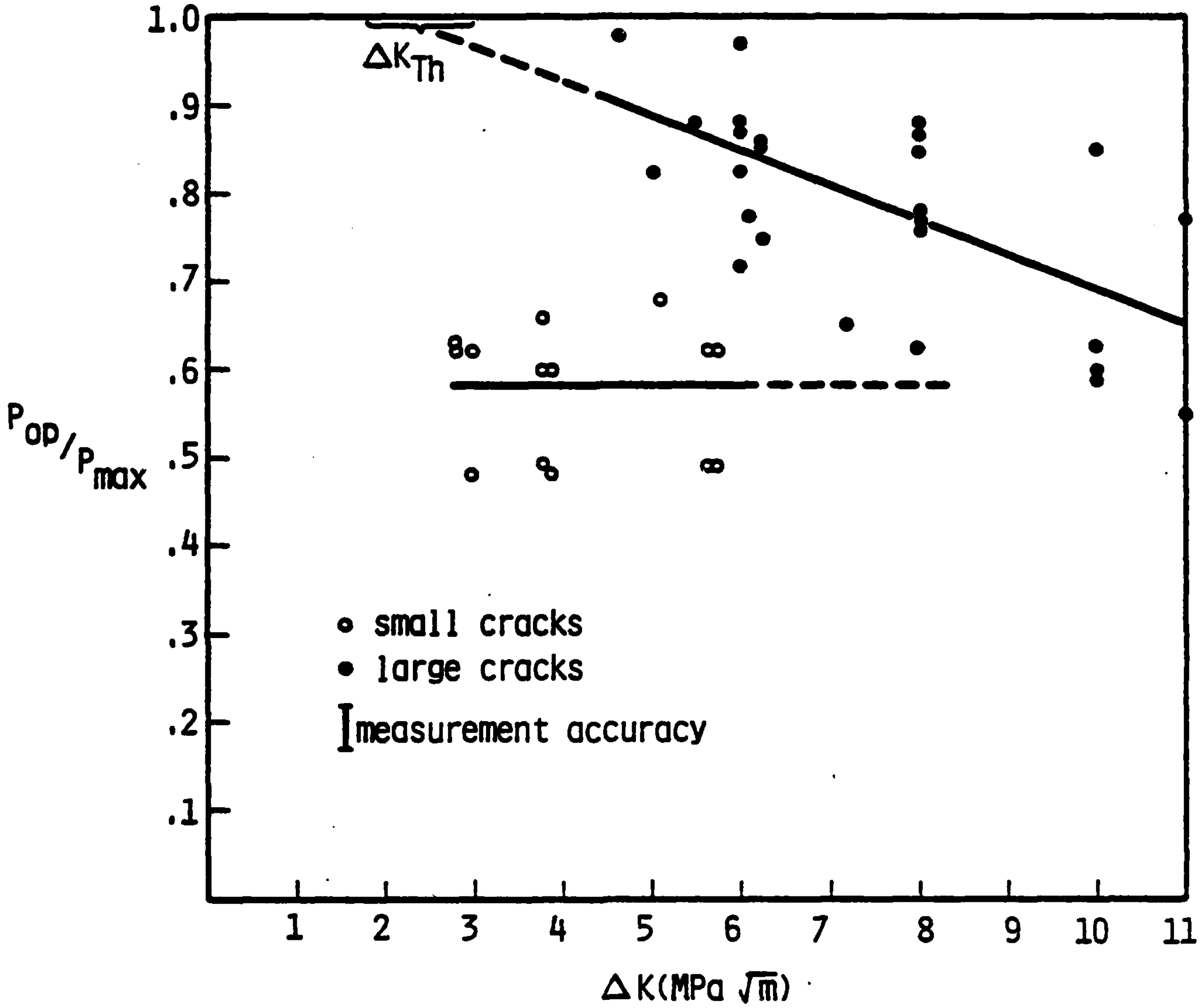

Figure 4. Ratio of crack opening load to maximum cyclic load versus ΔK, for large and small cracks.

III. List of Publications

1. "The Growth of Small Fatigue Cracks in 7075-T6 Aluminum," by J. Lankford, Fatigue of Engineering Materials and Structures, 5, pp. 233, 1982.

2. "The Effect of Environment on the Growth of Small Fatigue Cracks," by J. Lankford, Fatigue of Engineering Materials and Structures, 6, pp. 15, 1983.

3. "A Crack Tip Model for the Growth of Small Fatigue Cracks," by K. Chan and J. Lankford, Scripta Metallurgica, 17, pp. 529, 1983.

4. "Materials Aspects of Crack Tip Yielding and Subcritical Crack Growth in Engineering Alloys," by J. Lankford, Proceedings Fourth International Conference on the Mechanical Behavior of Materials, Vol. 1, Ed. J. Carlsson and N. G. Ohlson, p. 3, 1983.

5. "Near-Threshold Crack Tip Strain and Crack Opening for Large and Small Fatigue Cracks," by J. Lankford and D. L. Davidson, Concepts of Fatigue Crack Growth Threshold, The Metallurgical Society of AIME, New York, N.Y., ed. D. L. Davidson and S. Suresh (in press).

6. "The Influence of Crack Tip Plasticity in the Growth of Small Fatigue Cracks," by J. Lankford, D. L. Davidson, and K. S. Chan, Metallurgical Transactions (submitted).

IV. Participating Scientific Personnel

1. Dr. James Lankford (Staff Scientist, Principal Investigator)

2. Dr. David L. Davidson (Institute Scientist)

3. Dr. Kwai Chan (Senior Research Engineer)

4. Mr. James Spencer (Technician)

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2. J. Lankford, T. S. Cook, and G. P. Sheldon, "Fatigue Microcrack Growth in a Nickel-Base Superalloy," Int. J. Frac., 17, 1981, 143.

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VI. List of Illustrations

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